

## 1. Introduction

This document describes the National Institute of Standards and Technology (NIST) Measurement Service for providing calibrated photodiodes for absolute spectral responsivity in the ultraviolet (UV), visible, and near-infrared (NIR) spectral regions (200 nm to 1100 nm) and the special service of measuring photodetectors sent to NIST in the 200 nm to 1800 nm spectral region. This document supersedes NBS Special Publication 250-17 (1988), "The NBS Photodetector Spectral Response Calibration Transfer Program."

The theory, measurement system, operation, and transfer standards of the Spectroradiometric Detector Measurement Service are described in this publication. The traceability of the absolute spectral power responsivity scale to the High Accuracy Cryogenic Radiometer (HACR) and detailed uncertainty estimates are discussed. Also presented are the recently expanded list of absolute spectral power responsivity measurement services provided by NIST and the enhancements to its quality system to comply with ANSI/NCSL Z540-1-1994 [1].

The material presented in this document describes the equipment and procedures for the Spectroradiometric Detector Measurement Service as they exist at the time of publication. Improvements in the equipment, procedures, and services offered are continuous. The discussions in this document will be primarily directed at the procedures developed to measure the absolute responsivity of photodiodes supplied by NIST to customers. The procedures for characterizing customer-supplied detectors is a straightforward extension of the underlying procedures developed for the NIST furnished devices.

*Note: This document follows the NIST policy of using the International System of Units (SI). Only units of the SI and those units recognized for use with the SI are used. Equivalent values in other units may be given in parentheses following the SI values. The mechanical drawings in section 9.5 were originally prepared in English units and are presented without converting the values shown to SI units.*

## Background

Many radiometric, photometric, and colorimetric applications require the determination of the absolute spectral power responsivity of photodetectors. The absolute spectral power responsivity is the ratio of the photodetector's signal (amperes or volts) to the spectral radiant flux (watts) incident on the photodetector. The absolute spectral power responsivity is also referred to simply as the absolute spectral responsivity. Accurate measurement of absolute spectral power responsivity of photodetectors has been a service provided by the Optical Technology Division and its predecessors for over 20 years.

Various techniques have been employed to determine photodetector absolute spectral power responsivity [2, 3]. In the late 1970's a room-temperature electrical substitution radiometer (ESR), also known as an electrically calibrated radiometer (ECR), was used in conjunction with

lasers [4, 5] as the detector scale base. Relative uncertainties were reported on the order of 1.5 % to 5 % (3 standard deviation estimate<sup>1</sup>) over the spectral range from 390 nm to 1100 nm [6].

Note: This document follows, to the extent possible, the ISO Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, Switzerland, 1993). Since 1994, the NIST policy has been to conform to the *Guide* in reporting its activities, using an expanded uncertainty coverage factor (as defined in the *Guide*) of  $k = 2$ . See Ref. [7] for a detailed explanation of the NIST policy. Unless otherwise noted all uncertainties will be stated as  $k = 2$ .

A major advance came in the early 1980's with the silicon photodiode self-calibration techniques [8, 9] and the subsequent introduction of 100 % quantum efficient (QE) photodiodes [10] and their use as the basis for detector calibrations. These photodiodes were used in the development of the United Detector Technologies (UDT) QED-200<sup>2</sup> trap detector [11], which is a light-trapping device constructed of multiple, windowless, 100 % QE silicon photodiodes. The QED-200 had a limited spectral range (usually 400 nm to 750 nm) where it operated with 100 % QE, and suffered from limited dynamic range due to the relatively high bias currents used. The absolute spectral power responsivity was transferred to customers at this time via the Detector Response Transfer and Intercomparison Program (DRTIP). Customers would rent a radiometer from NIST and transfer the detector scale to their working standard(s). The scale relative uncertainty was typically 0.8 % to 6.0 % (3 standard deviation estimate) over the spectral range from 250 nm to 1100 nm [12].

A second generation trap detector (very similar to the commercially available Graseby Optronics QED-150) was later used as the basis for the NIST detector scale [13]. Both second generation trap detectors are constructed with a different type of silicon photodiode (Hamamatsu S1337-1010). They do not have 100 % QE, but the QE could be measured with the QED-200, and extrapolated with high accuracy over a large spectral range from 400 nm to 900 nm [14]. Relative uncertainties were reported on the order of 0.33 % to 1.0 % (3 standard deviation estimate) over the spectral range from 250 nm to 1100 nm (between 200 nm and 250 nm the relative uncertainty was reported as 5.0 %). The next advance came in the late 1980's when cryogenic ESRs were reported with improved uncertainties over the 100 % QE detector-based measurements [15, 16, 17]. The current state of cryogenic ESRs and future direction of detector-based radiometry are discussed in Refs. [18 and 19].

NIST has recently made changes to improve and expand the absolute spectral responsivity measurements it provides to its customers. The most significant change is to base the

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<sup>1</sup>The term "3 standard deviation estimate" or " $3\sigma$ " in the context of this paper is the estimated standard deviation multiplied by 3. Prior work at NIST was generally reported with " $3\sigma$ " uncertainties.

<sup>2</sup>Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

measurements on the NIST High Accuracy Cryogenic Radiometer [20]. The HACR is the U.S. primary standard for optical power. The scale of absolute spectral responsivity [21] is transferred by silicon photodiode trap detectors to working standards used with the NIST Visible to Near-Infrared [22] and Ultraviolet Spectral Comparator Facilities (hereafter referred to as the Vis/NIR SCF and UV SCF respectively in this document) where the Spectroradiometric Detector measurements are performed.

## 2. NIST Spectroradiometric Detector Measurement Service

This section describes the photodetector calibrations and measurements offered by the Optical Technology Division. A complete listing of the calibration services across all the measurement parameters offered by NIST can be found in the NIST Calibration Services Users Guide [23]. Current fees can be found in the Fee Schedule [24] which is updated annually and on the internet at the URL address: <http://ts.nist.gov/ts/htdocs/230/233/233.htm>.

### 2.1 Description of Measurement Services

There are two types of measurement services provided by NIST: Fixed Services and Special Tests. Fixed services (Service ID numbers ending in the letter C) have fixed measurement conditions and NIST issues a calibration report to the customer. Special tests (Service ID numbers ending in the letter S) have no fixed measurement conditions; are services that are under development; and/or are for unique customer-supplied test items. Service ID numbers 39071S through 39075S are currently in the process of being converted from Special Tests to Fixed Services (i.e., calibrations).

The present spectral range for photodetector absolute spectral responsivity measurements are from 200 nm to 1800 nm. Table 2.1 lists the services offered with typical measurement ranges and typical uncertainties. All services listed are provided routinely. The relative expanded uncertainties of the Spectroradiometric Detector Measurement Service are shown in figure 2.1 and table 2.2. See section 7 for a detailed explanation of the uncertainties.

**Table 2.1.** NIST Spectroradiometric Detector Measurement Services

Service ID number	Item of test	Range	Relative expanded uncertainty ( $k = 2$ )
39071S	Ultraviolet Silicon Photodiodes (UDT UV100)	200 nm to 500 nm	0.4 % to 13 %
39072S	Retest of Ultraviolet Silicon Photodiodes (UDT UV100)	200 nm to 500 nm	0.4 % to 13 %
39073S	Visible to Near-Infrared Silicon Photodiodes (Hamamatsu S2281)	350 nm to 1100 nm Can be extended to 200 nm	0.2 % to 4 % 0.2 % to 13 %
39074S	Retest of Visible to Near-Infrared Silicon Photodiodes (Hamamatsu S1337-1010BQ or S2281)	350 nm to 1100 nm Can be extended to 200 nm	0.2 % to 4 % 0.2 % to 13 %
39075S	Special Tests of Near-Infrared Photodiodes	700 nm to 1800 nm	0.5 % to 7 % <sup>†</sup>
39080S	Special Tests of Radiometric Detectors	200 nm to 1800 nm	0.2 % to 13 % <sup>†</sup>
39081S	Special Tests of Photodetector Responsivity Spatial Uniformity	200 nm to 1800 nm	0.0024 % to 0.05 % <sup>†</sup>

<sup>†</sup>Depends on photodetector and signal level.